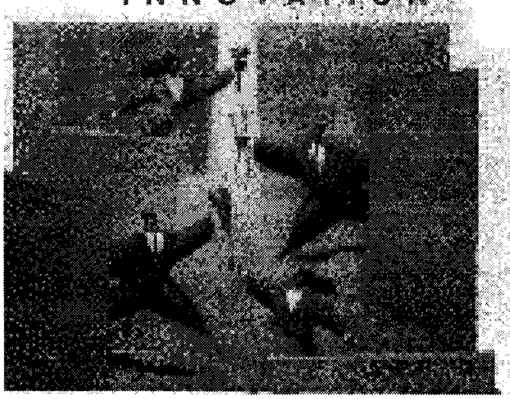

New and Improved
The Broadcast Interfrequency Biases

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"Better today than yesterday; better tomorrow than today." This often quoted maxim nicely describes the ongoing efforts by scientists and engineers to improve the Global Positioning System's accuracy, ease of use, and range of application. We have witnessed many improvements during the relatively short operational lifetime of GPS, such as a range of differential GPS techniques, more accurate satellite orbit ephemerides, and smaller, more powerful receivers. Researchers have also improved the models, or descriptions, of several biases that affect GPS observations including carrier-phase windup, satellite yaw attitude, and antenna phase-center offsets.

One of the latest GPS enhancements is an improvement of the interfrequency bias values contained in the navigation message broadcast by GPS satellites. Single-frequency receivers use these values to account for differential satellite hardware delays in the broadcast clock corrections. The new values were determined through a collaborative effort by a team of analysts from the National Aeronautics and Space Administration's Jet Propulsion Laboratory (JPL) — managed by the California Institute of Technology, The Aerospace Corporation, and several Department of Defense agencies. In this month's column, some of the team members discuss the importance of the interfrequency bias and how they obtained the new values.

In computing its position, a GPS receiver must account for several sources of error, such as atmospheric propagation delay, relativistic effects, and the offset of satellite clocks from GPS time. Each satellite's navigation message contains parameters describing the clock offsets. A GPS receiver uses these parameter values to compute the clock correction for each observation. Dual-frequency receivers directly employ such corrections; however, before a single-frequency receiver can use the computed offset, it must be adjusted to account for the differential group delay between the L1 and L2 frequencies. These delays, known as T_{GD}s, result from hardware differences in the onboard L1 and L2 signal paths and vary between space vehicles (SVs).

The GPS satellites include the L1–L2 satellite interfrequency biases in their navigation messages. The accuracy of the broadcast T_{GD} values directly affects a single-frequency user's navigation solution. Members of the ionospheric science community at National Aeronautics and Space Administration's (NASA's) Jet Propulsion Laboratory (JPL) and other institutions have been estimating satellite interfrequency biases since 1993 while extracting absolute measurements of line-of-sight ionospheric delay from dual-frequency GPS data. T_{GD} values derived by various groups in this community have shown good agreement, but discrepancies have always existed between the estimates and broadcast T_{GD} values, which are based on factory calibrations performed before a satellite's launch.

Considering these estimates, two questions come to mind: Do the estimated T_{GD} values provide a significant improvement in single-frequency navigation accuracy? And if so, which users are affected, and by how much? As always with GPS, the answers to these questions depend on the technique employed and the level of positioning accuracy desired.

The short answer is that presently the improvement in positioning accuracy is small but significant for some users, particularly single-frequency authorized users who ar not subject to selective availability (SA errors. High-accuracy applications, howeve are currently becoming more common, an as a result, desired accuracy levels will co tinue to increase in the future. Thus, properl removing biases such as T_{GD} can onl become more important.

Anticipating this need, a cooperativ analysis effort among the Air Force, JPL, an other members of the GPS community wa initiated in August 1998 to determine ne T_{GD} values. After validating the results, th GPS Joint Program Office (JPO) approved a update of the broadcast T_{GD} values. The fir set of new T_{GD} values based on JPL's est mates was uploaded to satellites in Apr 1999, and new values will be uploaded qua terly or as needed.

The new broadcast T_{GD} values do n impact dual-frequency navigation, of cours because T_{GD} does not enter into such positio calculations. The new values do, howeve affect dual-frequency users employing GP to measure the earth's ionosphere. Such use may want to characterize the ionosphere t monitor the space environment or to calibrat and remove ionospheric delays for other no GPS remote-sensing applications.

Civilian single-frequency users are als unaffected, because their standalone pos tioning errors are currently dominated by S errors (approximately 50 meters root-mea square) that mask the effect of inaccura T_{GD}s. However, single-frequency authorize receivers, such as the military Precisio Lightweight GPS Receiver (PLGR), as we as dual-frequency authorized receivers th revert to single-frequency mode, are not su ject to SA and can observe a 20–30 perce improvement in vertical position accura even though they are incurring residu ionosphere errors. When SA is turned off (b 2006, according to a presidential decisio directive), accurate T_{GD} compensation wi be important to civilian single-frequenc users as well.

T_{GD} errors will generally not impact differential GPS (DGPS) users because differential corrections (wide- or local-area) can compensate for the error, but there is one important exception to this rule. Wide-area DGPS (WADGPS) systems, such as the Federal Aviation Administration's (FAA's) Wide Area Augmentation System (WAAS), cannot optimally serve both single-frequency and dual-frequency users unless the broadcast T_{GD} values are accurate. To optimize the corrections for the single-frequency user, the fast (once per second) WAAS corrections can be adjusted to compensate for the difference between the broadcast and optimal T_{GD} values. Adjusting the corrections in this manner, though, is not optimal for dual-frequency users, who also benefit from the ability of WAAS corrections to remove SA errors.

In the following sections, we define T_{GD}, show how it is used in position calculation, describe the history of the effort to improve the broadcast T_{GD} values, discuss how and why JPL estimates the interfrequency biases, present some validation results, and, most importantly, delineate the benefits to the user community.

INTERFREQUENCY BIAS USE

The GPS Interface Control Document ICD-GPS-200 defines the T_{GD} parameter as the mean SV group delay differential in nanoseconds (measured by the SV contractor during factory testing) multiplied by a scaling factor. This correction term is for the benefit of single-frequency (L1 or L2) users who must adjust the received broadcast clock offsets before using them. Such adjustment is needed because the clock corrections are based on the effective pseudorandom noise (PRN) code phase with dual-frequency ionospheric corrections applied but without accounting for the group delay differential (that is, the ionosphere-free combination).

The value of T_{GD} is equal to the group delay differential multiplied by $1/(1-\gamma)$:

$$T_{GD} = \frac{1}{1-\gamma}\left(t_{L1} - t_{L2}\right)$$

in which t_{L1} and t_{L2} are the GPS times at which the L1 and L2 signals are transmitted from the SV, and γ equals the square of the L1 frequency (1575.42 MHz) divided by the L2 frequency (1227.6 MHz), or 1.64694:

$$\gamma = \left({}^{f_{L1}}\!/\!{}_{f_{L2}}\right)^2 = \left({}^{1575.42}\!/\!{}_{1227.6}\right)^2$$
$$= \left({}^{77}\!/\!{}_{60}\right)^2 = 1.64694$$

Correspondingly, $1/(1-\gamma)$ equals -1.54573.

The L1 user must modify the computed satellite clock correction (also known as the code phase offset), Δt_{SV}, with the equation

$$\left(\Delta t_{sv}\right)_{L1} = \Delta t_{sv} - T_{GD}$$

in which the value of T_{GD} is provided in subframe 1 of the broadcast navigation message. The L2-only user must multiply T_{GD} by γ in the above equation.

IMPROVEMENT HISTORY

NASA JPL developed the capability to solve for T_{GD} to enable precise ionospheric specification for NASA's Deep Space Network and the FAA's WAAS ionospheric correction algorithm. JPL had observed the discrepancy between the estimated values and the broadcast T_{GD} for many years without fully understanding the source of the differences, which range from 1 to 17 nanoseconds depending on the SV. Because the T_{GD} errors for some SVs are large enough to impact single-frequency positioning accuracy, JPL proposed that JPO update the broadcast values using JPL's estimates. The forum for this proposal was the August 1998 meeting of the Performance Analysis Working Group (PAWG).

A variety of high-end GPS users from the military, scientific, and civil communities continually strive for ever higher levels of accuracy. To bring together GPS satellite operators and analysts from this diverse community, the Air Force Space Command (AFSPC) and the satellite operators of the Second Space Operations Squadron (2 SOPS) host an annual PAWG meeting in Colorado Springs, Colorado. PAWG meetings aim to discuss observed GPS performance from a variety of perspectives, as well as short- and long-term system enhancements. These presentations and discussions run the gamut of satellite, ground station, and control system changes, including monitor station network upgrades, next-generation atomic frequency standards, Kalman-filter tuning, and broadcast navigation data.

After discussions about the cause of the discrepancies between the broadcast and estimated T_{GD} values, PAWG members from JPL, AFSPC, 2 SOPS, JPO, the National Reconnaissance Office (NRO), and The Aerospace Corporation informally met and decided on a course of action. The Aerospace Corporation organized independent validation tests of JPL's T_{GD} estimates. These tests were performed from August to November 1998. (Validation results from both the Air Force and JPL are discussed below.) In March 1999, JPL formally agreed to generate and deliver correctly-estimated T_{GD} values

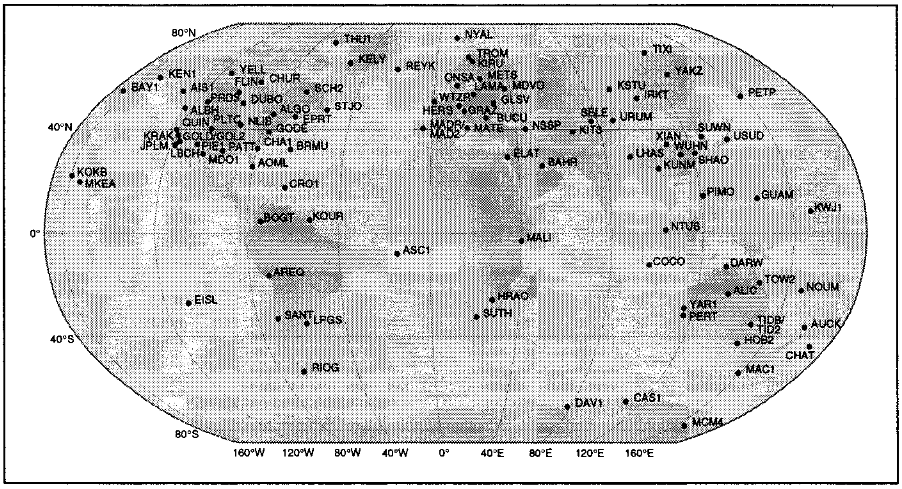

Figure 1. Site map of a subset of the global International GPS Service receiver network, showing the 98 receivers used to compute daily ionospheric maps

under NRO-sponsorship; 2 SOPS agreed to implement the satellite-specific database values and upload them in phases to each GPS satellite; and JPO, The Aerospace Corporation, and JPL agreed to analyze and validate the timing improvements to determine whether they accorded with expected results. In April 1999, the first set of new T_{GD} values were delivered and installed. As new satellites join the constellation and spacecraft configurations change, JPL will generate new T_{GD} values, which 2 SOPS will upload to the SVs after validation by the PAWG community.

THE NEW VALUES

JPL estimates T_{GD} values as a by-product of mapping the ionosphere using data provided by the International GPS Service (IGS). The IGS maintains a rapidly growing receiver network containing more than 220 globally distributed sites (see Figure 1), enabling continuous monitoring of ionospheric total electron content (TEC) on a global scale. Although the initial purpose of the IGS network was to measure baselines for geodetic and earthquake research, it has since been employed for many other applications, including remote sensing of the ionosphere and troposphere.

JPL has been exploiting this resource since 1993 when it first developed a global ionospheric mapping (GIM) algorithm. By using spatial interpolation and temporal smoothing between TEC measurements, combined with model information from climatological ionospheric models, global maps of vertical TEC can be produced with 5–60- minute resolution. The technique also estimates the instrumental L1–L2 biases in GPS receivers and satellite transmitters (that is, T_{GD}) simultaneously. A Kalman-type filter optimally combines the TEC measurements with model information, yielding a formal error map.

GIM Maps. Daily T_{GD} estimates are currently obtained from a GIM run using data from about 100 IGS receivers and solving for a global ionospheric map every 15 minutes. Figure 2 shows a typical global TEC map. The peak in the ionospheric delay occurs near the equator at 2:00 PM local time, corresponding to the fact that the sun's ultraviolet radiation and the earth's geomagnetic field strongly influence the ionosphere. Global TEC maps are useful for calibrating propagation delays and continuously monitoring the solar-terrestrial environment. Potential applications include global and regiona WADGPS systems, global calibration fc single-frequency satellite ocean altimetr missions, monitoring and prediction of spac weather conditions, delay corrections at sir gle-frequency satellite tracking stations an astronomical observatories, regional ionc spheric studies, and long-term monitoring c environmental change.

GIM and T_{GD}. The current GIM techniqu employs an extended slab model of the iono phere to estimate a map of vertical TEC on two-dimensional ionospheric shell at an alt tude of 450 kilometers. The vertical delay i modeled using bilinear or bicubic splines cor necting a set of vertex points uniformly di tributed on the shell. The vertex grid is fixe in a solar-geomagnetic coordinate system i which latitude is measured from the geomag netic equator and the longitude is nearly sur fixed, because the ionosphere is less variabl in this reference frame than in an earth-fixe one. The technique models dual-frequenc GPS observations as the sum of the receive and satellite instrumental biases (T_{GD}) an the measured slant TEC. Because the instru mental biases are geometry-independent bu the ionospheric delay is a function of satellit elevation and azimuth, the filter solution ca separate the biases from the ionospheri effect. An obliquity factor that assumes a extended slab approximation enables conve sion of the slant TEC to an equivalent vertic TEC at the shell pierce point.

For each measurement update, the tech nique re-estimates the vertical TEC at ever grid point but models the vertex paramete as "random walk" stochastic processes in

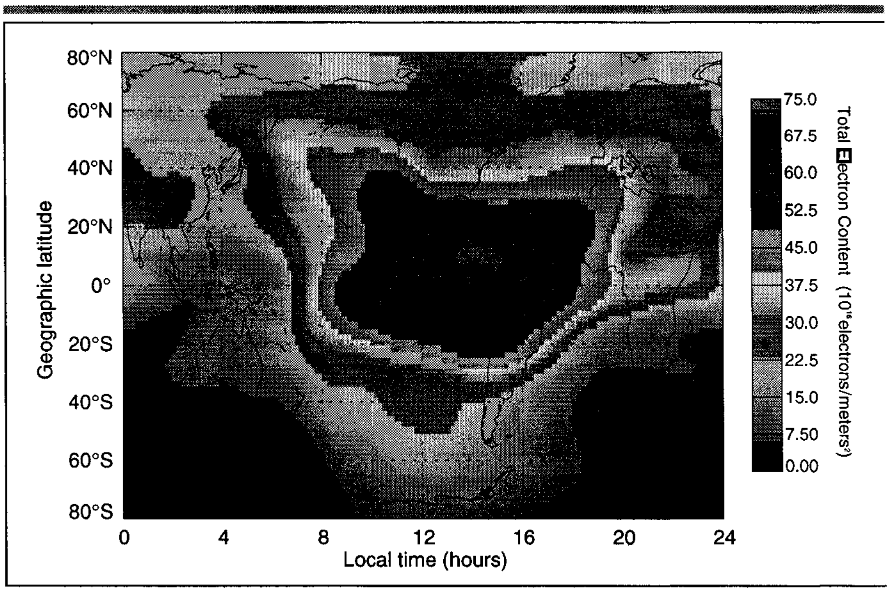

Figure 2. A typical global ionospheric map showing the vertical total electron content distribution between 1915 and 1930 Universal Time on May 29, 1999

Kalman-type parameter estimation filter so that a short history of measurements contributes to the current estimate. Because the spline basis functions overlap, the vertex TEC values and the values at adjacent grid points spatially correlate. Assuming the receiver and satellite biases are constant for 24 hours, the filter yields daily estimates of T_{GD}. (One could increase the frequency of the estimates to provide values every 3–6 hours if required.) By using one or more calibrated receiver biases to separate the satellite and receiver biases, one can determine the overall level of the satellite biases. The contractor implementing WAAS for the FAA is using a modified version of the GIM algorithms to derive T_{GD} values in a similar manner.

Figure 3 shows a 500-day time series of T_{GD} estimates for a subset of the satellites (PRNs 1–6) from January 1, 1998, to June 6, 1999. The day-to-day reproducibility of the T_{GD} estimates is 0.2–0.4 nanosecond (1 sigma, in T_{GD} units including the factor of 1.54573). The values have been constant to this accuracy level for months, if not years. The T_{GD} values reported by JPL are an average of 10 daily estimates, thus reducing the random noise in the estimates. During the history of JPL's estimates, several satellites have changed values because of vehicle configuration (transmitter) changes. For example, SV number (SVN) 40's bias abruptly shifted from −0.7 to −1.8 nanoseconds on November 29, 1996, when the SV configuration was changed to use the alternate L-band subsystem.

Table 1. Jet Propulsion Laboratory (JPL)–estimated satellite-broadcast differential group delay (T_{GD}) values in nanoseconds for April 1999

PRN number	Space vehicle number	JPL T_{GD} estimate	Multiple of 0.4657	Quantization error	New broadcast T_{GD}	Old broadcast T_{GD}
1	32	−3.34	−7	−0.08	−3.26	0.47
2	13	−1.49	−3	−0.09	−1.40	−2.33
3	33	−4.60	−10	0.05	−4.66	1.40
4	34	−6.40	−14	0.12	−6.52	2.33
5	35	−4.40	−9	−0.21	−4.19	2.33
6	36	−5.12	−11	0.01	−5.12	1.86
7	37	−1.77	−4	0.10	−1.86	−0.93
8	38	−4.12	−9	0.07	−4.19	1.40
9	39	−5.62	−12	−0.03	−5.59	5.12
10	40	−1.86	−4	0.01	−1.86	−1.86
13	43	−12.20	−26	−0.09	−12.11	5.59
14	14	−2.41	−5	−0.08	−2.33	−2.33
15	15	−2.14	−5	0.19	−2.33	−0.93
16	16	−0.39	−1	0.07	−0.47	−2.33
17	17	−1.99	−4	−0.13	−1.86	−0.47
18	18	−4.98	−11	0.14	−5.12	−0.93
19	19	−2.98	−6	−0.19	−2.79	−3.26
21	21	−2.27	−5	0.06	−2.33	−0.93
22	22	−3.97	−9	0.22	−4.19	0.93
23	23	−2.86	−6	−0.07	−2.79	−0.47
24	24	−0.99	−2	−0.05	−0.93	−0.93
25	25	−7.52	−16	−0.07	−7.45	1.86
26	26	−6.57	−14	−0.05	−6.52	0.00
27	27	−4.25	−9	−0.06	−4.19	0.47
29	29	−7.31	−16	0.14	−7.45	2.33
30	30	−8.10	−17	−0.18	−7.92	3.26
31	31	−6.09	−13	−0.03	−6.05	1.40

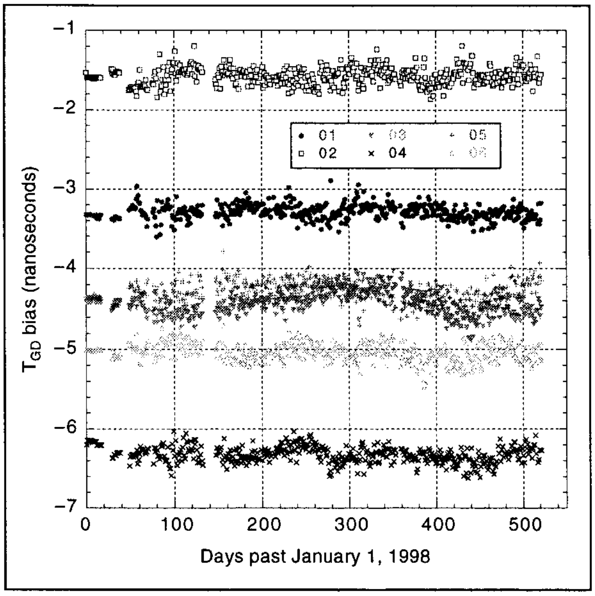

Figure 3. Day-to-day reproducibility of the daily differential group delay (T_{GD}) estimates for selected satellites during two years

New versus Old. Table 1 summarizes the JPL estimates and the broadcast T_{GD} values by PRN/SVN as of April 1999. The broadcast values of T_{GD} have a resolution (quantization) of 2^{-31} seconds or about 0.4657 nanosecond, which is slightly less than the accuracy of the T_{GD} estimates (0.2–0.3 nanosecond). The new broadcast values are based on a 10-day average of JPL's estimates from March 11–20, 1999. Because each value is a multiple of 0.4657 (column four), the new broadcast values vary from the estimates by the quantization error (column five), with the largest difference being 0.22 nanosecond for SVN 22.

The last column of Table 1 shows the old broadcast T_{GD} values for comparison with the new ones. The discrepancies range from +1.9 nanoseconds for SVN 16 to −17.7 nanoseconds fc SVN 43 (the only Block IIR SV currently i orbit), with a mean difference of −4. nanoseconds and a standard deviation of 4. nanoseconds. These differences are substar tial and, as we will see below, can cause significant reduction in positioning accurac

Suspicious of the large differences, Th Aerospace Corporation obtained the factor calibrations from the SV contractors an found that the old broadcast T_{GD} values wer not scaled properly. Scaling the factory cal brations properly (multiplying by −1.5457 the agreement between JPL's estimates an the prelaunch calibrations greatly improve the mean difference and standard deviatio become 3.5 and 2 nanoseconds, respectivel

VALIDATION

The ionospheric community has extensivel validated the new T_{GD} values through yeai of data processing. But the most direct test c their usefulness to the GPS community as whole is to quantify the resulting improve ment in positioning accuracy. As mentione earlier, SA errors usually mask the effect c T_{GD} biases. However, the benefits to singl

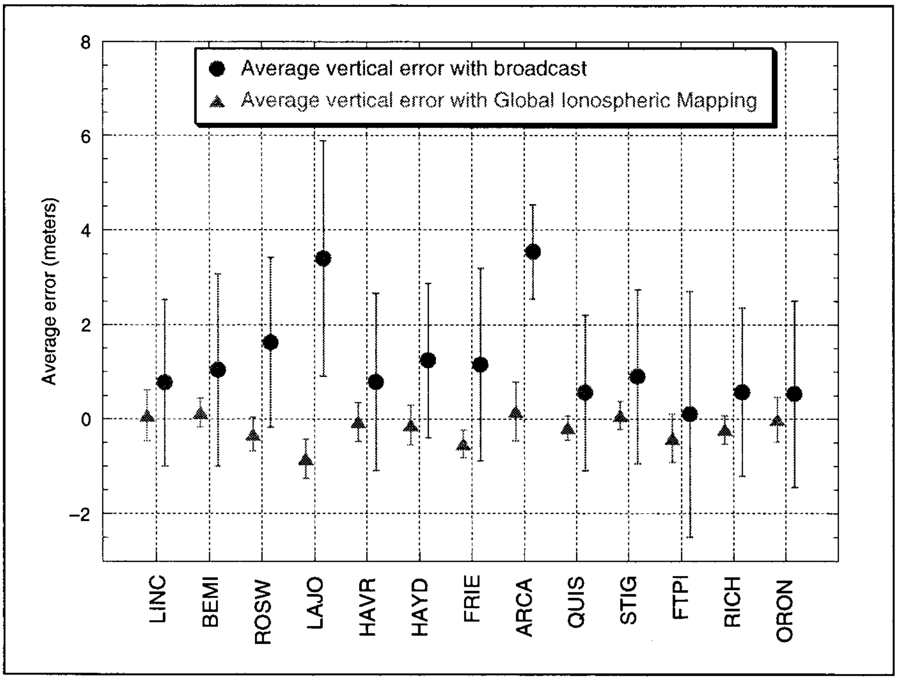

Figure 4. Effect of differential group delay on single-frequency vertical positioning error for 14 known receiver locations using both the old and new broadcast values

frequency positioning users are visible in two particular scenarios: WAAS users for whom the fast corrector removes SA errors and authorized P(Y)-code users such as those employing PLGR receivers.

WADGPS. JPL first observed the effect of using incorrect T_{GD} values in 1996 while developing a prototype, real-time WADGPS system. Using 1-second data from a real-time receiver network in the contiguous United States, as well as JPL-developed algorithms for the satellite orbit, fast clock, and ionosphere corrections, JPL demonstrated and validated an operational WADGPS system, subsequently transferring the technology to a private company. Another company is using modified versions of the same algorithms to implement the FAA's WAAS.

Because, in addition to mitigating SA effects, WADGPS removes signal-in-space (SIS) errors and a majority of ionospheric delay biases, the use of incorrect T_{GD} values is quite evident. Figure 4 shows the effect of T_{GD} on vertical positioning error on a GPS network by comparing positions computed using old T_{GD} broadcast values with those calculated using JPL's GIM estimates. The network's 14 receivers at known locations were point positioned every second using only single-frequency GPS data and WADGPS correctors, thereby simulating a user receiver. For this period in December 1996, root-mean-square position error was better than 0.3 meter for the east and north components and 0.6 meter for the vertical component when using the GIM-based T_{GD} values.

Figure 4 also compares the mean vertical positioning error and the standard deviation (error bars) for the two sets of T_{GD} values. Using the old broadcast T_{GD}, the mean vertical errors are biased away from ground truth by 1–3 meters, and the standard deviations are 2–5 meters. Although a WADGPS's fast corrector could be adjusted to compensate for the difference in the T_{GD} values, the fast corrector would no longer be optimal for potential dual-frequency users.

Single-Frequency. The second validation scenario involved using a single-frequency authorized PLGR receiver. Before making a decision to modify the broadcast message, JPO requested an independent field test to validate the JPL-estimated T_{GD} values. The Aerospace Corporation organized tests conducted by the U.S. Air Force 746th Test Squadron at Holloman Air Force Base, New Mexico, on November 20, 1998. Using 21.5 hours of 30-second pseudorange data from the fixed PLGR, positioning performance was compared using the old broadcast T_{GD}s versus the JPL-estimated values.

Table 2. Positioning error for a Precision Lightweight GPS Receiver using old and Jet Propulsion Laboratory (JPL)–determined differential group delay values

	System error		User segment error	
	Horizontal	Vertical	Horizontal	Vertical
Old	4.58	6.13	3.00	4.96
JPL	4.50	5.16	2.31	3.10

Table 2 summarizes the horizontal an vertical components of the positioning errc as well as the user segment error. Th positioning error, or total system erro includes the SIS errors (space and contro segment errors), residual errors in the broac cast single-frequency ionosphere model, T_G errors, and other user equipment erro (receiver noise, multipath, and tropospheri effect). The user segment error was com puted by removing the SIS error, employin a posteriori knowledge of satellite orb and clock errors. The JPL-estimated T_{GD} reduced the vertical positioning error b approximately 20 percent. Even more sig nificant was the impact on user-segmen errors, which were reduced by more tha 20 percent in the horizontal component an by almost 40 percent in the vertica Although new military handheld receive will be dual frequency, current PLGRs wi remain in service for five to 10 years, so thes accuracy improvements will provide a lastin benefit to that community.

ADDITIONAL BENEFITS

There are two other immediate benefits t using correct T_{GD} values: improved consis tency in GPS time transfer and more accurat measurement of absolute slant ionospheri delay from dual-frequency GPS receivers fo ionospheric research.

Time Transfer. The U.S. Naval Observator (USNO) employs GPS to transfer tim between precise time standards at differe locations. As part of these operations, it mon itors the difference between Coordinate Universal Time (UTC) at USNO and GP time (UTC minus GPS time) using both sin gle- and dual-frequency receivers. Prior t the April 1999 update of the broadcast T_{GD}s there was an offset between values provide by the two types of receivers (single minu dual) of −9.78 nanoseconds (mean differenc from February 21, 1997, to March 31, 1999 After the update, the offset was reduced t −0.35 nanoseconds (mean difference fro May 1, 1999, through July 2, 1999). Th improved consistency between the two time transfer techniques is a significant benefit t the timing community, and it provides additional evidence that the new T_{GD} estimates are correct.

Ionospheric Research. Ionospheric scientists have been estimating and distributing sets of interfrequency biases for years, but having an accurate set of T_{GD}s in the broadcast navigation message is still a benefit to this community. To compute absolute slant ionospheric delays from the dual-frequency GPS observables (pseudorange and carrier phase), one must know the interfrequency biases for the satellites and the receiver. The receiver bias can be determined in a variety of ways: by direct instrumental calibration, by comparison to a calibrated receiver, or by obtaining the value from the receiver manufacturer. Now that the correct satellite biases are broadcast, every GPS receiver is potentially source of accurate ionospheric measure ments. Even when a receiver bias calibratio is not available, one can often set the absolut level of the ionosphere by adjusting a fre parameter on physical grounds — th approximately constant nighttime TEC leve

FUTURE DEVELOPMENTS

With the advent of enhanced, semicodeles tracking techniques in modern receiver there are potentially two range observables L1: one based on the C/A-code (denoted her as CA1 or C1) and another based on the P(Y code (denoted P1). Thus, there are two poss ble dual-frequency combinations, P1–P2 an C1–P2, and potentially two different interfre quency biases in the signal paths of bot satellites and receivers. These two biases a related by the C1–P1 bias, which JP researchers have found to vary between sate lites by as much as 3 nanoseconds.

Currently, JPL's T_{GD} estimates, and there fore the broadcast values, are based o P1–P2. Consequently, T_{GD} compensation i correct for single-frequency authorized (P1 users but not optimal for civilian (C1) user As a result, we now need to provide compen sation for two different biases. In additio when the C/A-code becomes available on L in a future generation of GPS, the iono spheric community will have to solve for third interfrequency bias (C1–C2). Compen sation for this differential group delay will b required for dual-frequency civilian use (using C1 and C2) because the broadcas clock offsets will still be based on the iono sphere-free combination of P1 and P2. T achieve the greatest possible accuracy in a GPS applications, the user community mu continue to refine its knowledge of all c these biases.

CONCLUSIONS

As a result of a cooperative effort involvin numerous members of the GPS communit the broadcast navigation message now con tains accurate T_{GD} biases, and the values wi be updated as necessary. Demonstrated bene fits include improved positioning accurac for single-frequency authorized users, opt mal use of WADGPS correctors by both sin gle- and dual-frequency users, improve consistency in GPS time transfer, and mor accurate GPS-derived ionospheric measure ment. When SA is turned off, correct T_G compensation will provide better positionin for civilian users as well.

This success story is just one example c how scientific GPS applications, such a ultra-precise (subcentimeter) geodesy an

FURTHER READING

For details about correcting GPS measurements for interfrequency bias and other effects, see

- *Interface Control Document, Navstar GPS Space Segment/Navigation User Interfaces, ICD-GPS-200,* Revision C (IRN-200C-002), published on behalf of the Department of Defense by ARINC Research Corp., El Segundo, California, 1997. This document is available as a PDF file from the U.S. Coast Guard's Web site: <http://www.navcen.uscg.mil/gps/geninfo/gpsdocuments/icd200/icd200c.pdf>.

For further details about interfrequency bias improvements, see

- "GPS Satellite Interfrequency Biases," by C.H. Yinger, W.A. Feess, R. Di Esposti, A. Chasko, B. Cosentino, D. Syse, B. Wilson, and B. Wheaton, published in the *Proceedings of The Institute of Navigation 55th Annual Meeting,* Cambridge, Massachusetts, June 1999.

For discussions about JPL's approach to ionosphere mapping and interfrequency bias estimatation, see

- "A New Method for Monitoring the Earth's Ionospheric Total Electron Content Using the GPS Global Network," by A.J. Mannucci, B.D. Wilson, and C.D. Edwards, published in the *Proceedings of ION GPS-93,* the 6th International Technical Meeting of the Satellite Division of The Institute of Navigation, Salt Lake City, Utah, September 22–24, 1993, pp. 1323–1332.
- "A Global Mapping Technique for GPS-Derived Ionospheric Total Electron Content Measurements," by A.J. Mannucci, B.D. Wilson, D.N. Yuan, C.H. Ho, U.J. Lindqwister, and T.F. Runge, published in *Radio Science,* Vol. 33, No. 3, May–June 1998, pp. 565–582.
- "GPS and Ionosphere," **[[Brian: no "the"?]]** by A.J. Mannucci, B.A. Iijima, U.J. Lindqwister, X. Pi, L. Sparks, and B.D. Wilson, which will appear in *Review of Radio Science,* published by the International Union of Radio Science, August 1999.

For a discussion of wide-area differential GPS and the role of improved interfrequency bias values, see

- "A Real-Time Wide Area Differential GPS System," by W.I. Bertiger, Y.E. Bar-Sever, B.J. Haines, B.A. Iijima, S.M. Lichten, U.J. Lindqwister, A.J. Mannucci, R.J. Muellerschoen, T.N. Munson, A.W. Moore, L. Romans, B.D. Wilson, S.C. Wu, T.P. Yunck, G. Piesinger, and M. Whitehead, published in *Navigation,* Vol. 44, No. 4, pp. 433–447, 1997.

For the latest estimates of interfrequency biases along with any late-breaking news concerning differential group delay values, see

- Jet Propulsion Laboratory, Ionospheric and Atmospheric Remote Sensing Group's web site: <http://sideshow.jpl.nasa.gov/gpsiono>.

ionospheric and tropospheric remote sensing, often improve positioning capabilities for the everyday GPS user. The demand for ever greater fidelity in cutting-edge science leads to more accurate calibration and modeling of GPS biases — whether they are T_{GD} biases, carrier-phase windup, satellite yaw attitude, or antenna phase-center offsets. Ultimately, all users benefit.

ACKNOWLEDGMENTS

The authors would like to thank all of the involved parties at JPL, The Aerospace Corporation, U.S. Air Force 746th Test Squadron, NRO, AFSPC, 2 SOPS, and JPO for contributing to this work. We would also like to thank Lara Schmidt at the U.S. Naval Observatory for details about the effect of interfrequency biases on time transfer. JPL's contribution to the research described in this article was performed under contract with NASA. ■

MANUFACTURERS

The NASA's Jet Propulsion Laboratory (JPL) performed differential group delay bias tests using the Precision Lightweight GPS Receivers manufactured by **Rockwell Collins** (Cedar Rapids, Iowa). JPL researchers also made use of a wide-area differential GPS system operated by **Satloc** (Scottsdale, Arizona), a unit of **Communication Systems International** (Calgary, Alberta, Canada), and developed, in part, with help from JPL. **Raytheon Systems Company** (Arlington, Virginia) is developing and fielding the Federal Aviation Administration's Wide Area Augmentation System using JPL-developed algorithms for satellite orbit, fast clock, and ionosphere corrections.**[[Brian: is all this correct?]]**

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"Innovation" is a regular column featuring discussions about recent advances in GPS technology and its applications as well as the fundamentals of GPS positioning. The column is coordinated by Richard Langley of the Department of Geodesy and Geomatics Engineering at the University of New Brunswick, who appreciates receiving your comments as well as topic suggestions for future columns. To contact him, see the "Columnists" section on page 4 of this issue.